

# INVESTIGATING THE ORIGIN AND EVOLUTION OF VENUS WITH DESCENT PROBE MASS SPECTROMETRY

William B. Brinckerhoff<sup>(1)</sup> and Paul R. Mahaffy<sup>(1)</sup>

<sup>(1)</sup>NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA, Email: William.B.Brinckerhoff@NASA.gov

## ABSTRACT

Future missions to Venus will require a focused investigation of the atmospheric composition, to complete the story of its formation and evolution drafted by the probes of the 1970s and 1980s and developed further by recent missions such as Venus Express. Priority measurements include the mixing ratios and isotope ratios of all noble gases, detection of trace species in the lower atmosphere including sulfur compounds, and light element isotope systematics. We present a concept for a highly sensitive neutral mass spectrometer (NMS) investigation that can make these measurements on a descent probe or other *in situ* atmospheric mission. The NMS investigation is a key element of the Surface and Atmosphere Geochemical Explorer (SAGE) mission under study within the NASA New Frontiers program.

## 1. BACKGROUND

The exploration of Venus continues to be a top priority of planetary science. Venus is the most mysterious of the terrestrial planets, with a complex surface enshrouded in a thick atmosphere, remarkably different from the Earth's despite the gross similarities between these "twin planets". It is unknown if this apparent divergence was intrinsic, programmed during accretion from distinct nebular reservoirs, or a consequence of either measured or catastrophic processes during planetary evolution. Even if the atmosphere of Venus is a more "recent" development, its relationship to the resurfacing of the planet's enigmatic surface is not well understood. Resolving such uncertainties directly addresses the hypothesis of a more clement, possibly water-rich era in Venus' past as well as whether Earth could become more Venus-like in the future.

Directly distinguishing among models of the nebular reservoir of Venus and of the subsequent evolution of its atmosphere has been identified by numerous consensus reviews as critical to our further understanding of the origins of the terrestrial planets [1-3]. The Pioneer Venus large probe [4-9] along with the Venera [10,11] and Vega [12] landers, all outfitted with mass spectrometers, provided seminal *in situ* atmospheric analyses, suggesting that Venus suffered a distinct pattern of losses from that of Earth and Mars

but may still have formed from essentially similar starting materials. A lack of systematic isotopic data and some inconsistencies among measurements of noble and trace reactive gas abundances by these probes however point to the need for a new, focused analysis using a Venus-specific gas processing system coupled to a highly sensitive and quantitative mass spectrometer. This need has been amplified by the tantalizing results from the Venus Express orbiter mission [13], with evidence of latitudinal gradients in species such as CO and OCS [14,15], and indications of recent volcanic activity [16].

Here we present details of a neutral mass spectrometer (NMS) investigation of the abundances and isotope ratios of a wide range of atmospheric chemical species at Venus. NMS directly addresses key objectives of Venus atmospheric science with a design tailored for the quantitative noble gas, light element, and trace species measurement requirements of various potential *in situ* missions. When combined with other complementary investigations, we may anticipate that NMS data will lead to significant improvements in our understanding of the history and current state of Venus.

The focus of this report is to describe the objectives, capabilities and operational profile of NMS as it would be implemented on a descent probe type mission. On such a platform, NMS is expected to operate continuously as the probe approaches the surface of Venus, making measurements as a function of altitude. The time available to conduct the investigation and transmit data could be quite short (potentially on the order of one hour). As such exquisite attention to the sensitivity of the instrument and the nature of its background is required for the quantitative analysis of trace species. The NMS instrument is also compatible with other platforms and scenarios, such as a long-duration balloon or a surface investigation, with little change.

## 2. MEASUREMENT OBJECTIVES

While a broad review of the scientific drivers for a detailed atmospheric composition is beyond the scope of this report (see, e.g., [1] and [17-19]), it is useful to touch on a few example objectives that have direct implications for mass spectrometry requirements.

## 2.1 Xenon

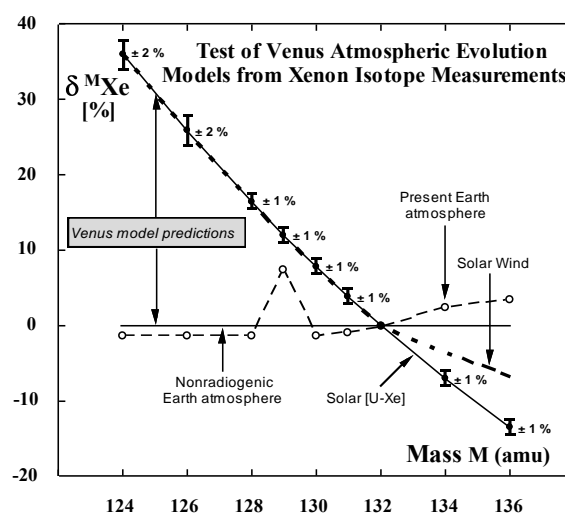
As the heaviest noble gas, Xe serves as a sensitive measure of the original volatile inventory of Venus, relative to Earth, Mars, and Jupiter. Pioneer Venus noble gas results showed that Venus follows analogous monotonic depletions of noble gases from initially solar compositions compared with Earth and Mars. However, the mechanisms of escape from Venus and the relationship to the intriguing isotopic fractionation of terrestrial Xe in particular remain unconstrained. Precise isotope ratios of  $^{124}\text{Xe}$  through  $^{136}\text{Xe}$  to  $^{132}\text{Xe}$  at Venus have the potential to distinguish between two “end member” fractionation scenarios (Fig. 1) for the terrestrial planets. One in which Xe escaped hydrodynamically from Earth and Mars under bombardment from  $\text{H}_2$  excited by extreme ultraviolet (EUV) radiation of the young sun [20] or large impacts might yield nearly solar-like Xe isotopes at Venus. Alternatively an Earth-like pattern of  $\delta^M\text{Xe}$  would indicate a common later source of Xe such as impact of very cold (noble-gas retaining) comets from the outer solar system [21,22]. Precisions of 1-2% achievable with NMS readily identify these sources and indeed could reveal hybrid scenarios in which the character and timing of Xe gains and losses at Venus are diagnostic of a peculiar history. Moreover, such precisions are required to understand if the primordial Xe of Venus can be explained by a chondritic “universal Xe” (U-Xe) or something closer to the solar wind composition, which would differ only by a few % at the heavier isotopes [23].

## 2.2 Neon and Argon

Abundances and isotopes of Ne and nonradiogenic Ar may similarly reveal a significant role of impact delivery of volatiles to Venus. The very high abundances of these noble gases as measured by Pioneer Venus indicate admixing with a source of either solar wind or cometary provenance, although distinguishing these requires reducing the uncertainties in  $^{36}\text{Ar}/^{38}\text{Ar}$  and in  $\delta^{21}\text{Ne}$  and  $\delta^{22}\text{Ne}$  to less than ~1-2%. Such precise measurements may also bolster the Xe evidence for fractionation and/or reveal new subtleties.

## 2.3 Nitrogen

Although the  $^{15}\text{N}/^{14}\text{N}$  ratio is known for Mars and Earth, there is a substantial uncertainty [24] in the Venus ratio of +20% of the terrestrial value of  $3.7 \times 10^{-3}$ .  $^{15}\text{N}/^{14}\text{N}$  in solar system reservoirs varies substantially and the value determined at Jupiter by the Galileo Probe Mass Spectrometer [25] is substantially lower than the Earth, Titan, and Mars. The solar wind values that could confirm the protosolar value from the Genesis mission are still in dispute [26,27]. For Mars, the heavy nitrogen values have been explained as evidence of escape processes [28], and the Venus



**Fig. 1** The non-radiogenic Xe composition on Venus could be solar (U-Xe)-like [20,23] or resemble the non-radiogenic terrestrial atmosphere [21,22]. The error bars show the ability of isotopic measurements with the  $\pm 1\sigma$  precision specified in Table 1 to distinguish between the two, or to identify intermediate compositions. Solar wind-Xe (heavy dashed curve) is arguably also a candidate composition for Venus Xe. It is isotopically identical to U-Xe except for excesses, relative to U-Xe, in  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$ . Precision of  $\pm 1\%$  would distinguish SW-Xe from U-Xe at these isotopes. Figure adapted from Pepin, 2006 [23].

measurement will further constrain escape processes in the terrestrial planets.

## 2.4 Sulfur

The sulfur cycle is a central chemical process in the atmosphere of Venus, involving chemical exchange with surface reservoirs, thermochemical reactions in the lower atmosphere, formation of sulfuric acid droplets in the clouds, and photochemistry at higher altitudes [29-33]. Active volcanism may be contributing sulfur compounds to the present atmosphere [16, 32]. The present sulfur inventory of the lower atmosphere is dominated by  $\text{SO}_2$ ,  $\text{OCS}/\text{COS}$ , and  $\text{H}_2\text{S}$ , at a few to hundreds of parts per million. While some vertical profile data are known from Venera and Venus Express, a detailed understanding of the timescales and stability of their current sources and sinks will require simultaneous measurements of their profiles at sub-scale height resolution, achieved by NMS. Moreover, our full assessment of the Venus greenhouse and possible significant surface temperature variability [34] requires sulfur measurements as well as a complete accounting of any other sulfur species. Notably, the detection of significant concentrations of allotropic S ( $\text{S}_2$ ,  $\text{S}_3$ ,  $\text{S}_4$ , and  $\text{S}_8$ ) [35] along with chlorine compounds [36] could strongly constrain models of the composition and stability of the Venus cloud layers. Finally, S isotopic data ( $^{34}\text{S}$  and possibly  $^{33}\text{S}$ ) in any of these species to within a few % would be highly desirable.

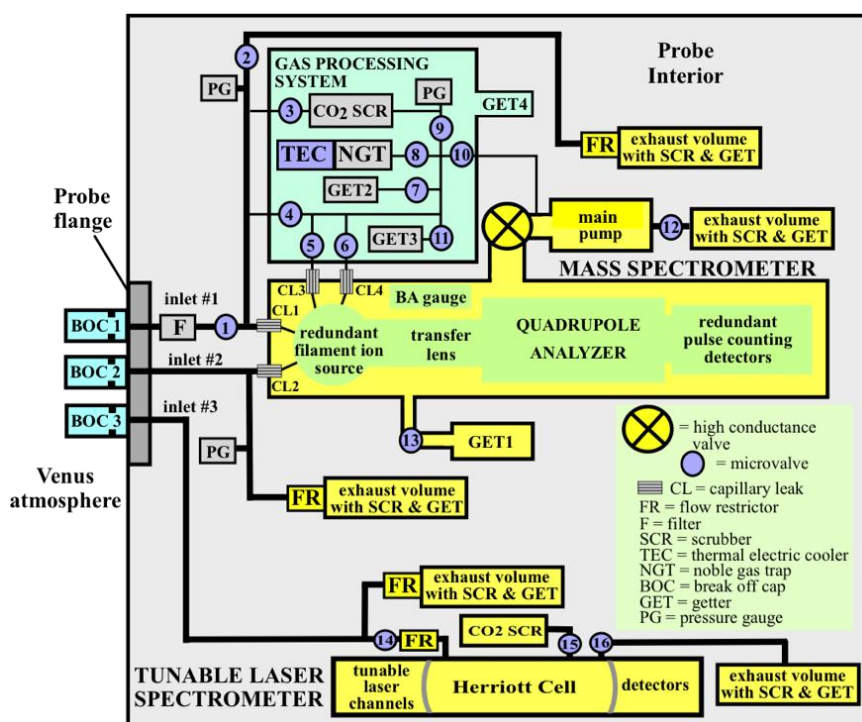
### 3. NMS INSTRUMENT OVERVIEW

Neutral mass spectrometers have been employed on entry probes of Jupiter, Venus, Mars, and Titan. This technique provides a broad chemical survey of major and trace species and is the only practical technique to measure the noble gas elemental and isotopic ratios [37,38] that are important for understanding atmospheric evolution.

The NMS investigation on the SAGE Venus lander mission exemplifies the short-duration descent probe implementation of a thorough atmospheric analysis with mass spectrometry. SAGE was selected as one of three New Frontiers mission concepts to undergo a Phase A study. Following a second review, NASA will select one of the three concepts to proceed to flight implementation. The SAGE mission is summarized separately in this volume by Bienstock *et al.* The NMS instrument is accommodated entirely within the pressure vessel of the lander, and exposed to the Venusian atmosphere solely through constricted inlets which are protected prior to use by pyrotechnic breakoff caps mounted on the outside of the vessel. The core of the NMS is a 2 to 550 Dalton (Da) mass spectrometer incorporating an electron impact ion source similar to the one used on the Galileo Probe Mass Spectrometer (GPMS) [39], a quadrupole mass analyzer, and dual channel electron multiplier

detectors. The mass range of the NMS enables measurement of all the noble gases, simple molecular species, and more complex species such as S<sub>8</sub> (molecular weight 256 Da) if these are present in the atmosphere. Two independent gas inlets permit dedicated sampling operations above and below the cloud layer, and their geometry enables direct beaming of reactive species into the NMS ionization region during the lander descent - minimizing chemical wall interactions. Redundant filaments are employed in the source. In the unlikely event of a filament or detector failure the backup is automatically switched into operation during descent. Chemical getters pump the reactive constituents, and an ion pump removes the inert gases. To maintain a very low background pressure in the instrument, the sampling system and the sensor are kept under high vacuum before descent stage entry into the atmosphere of Venus. Static micro-electromechanical (MEMS) type pressure transducers are used to monitor the inlet line and purification cell pressures during operation.

The NMS gas flow diagram is shown in Fig. 2. The ends of the inlet tubes, exposed after pyrotechnic breakoff, extend into the free flow region to eliminate ingestion of contamination gases or particles released from the surface of the descent probe. The breakoff assemblies themselves do not introduce contamination to NMS based on previous test and flight experience.



**Fig. 2** Schematic block diagram of a Venus descent probe neutral mass spectrometer (upper section) and a tunable laser spectrometer (lower section) showing gas flow connections. BA = Bayard-Alpert type pressure gauge. In this concept the pumped and excess gas load is captured with previously-evacuated exhaust volumes sized for the mission profile, removing any risk of backflow into NMS with probe or Venus venting schemes.

Dynamic pressure forces atmospheric gas to flow through chemically passivated plumbing and past pressure reducing leaks mounted in the ion source. The leaks comprise bundled arrays of glass capillaries (typically seven capillaries per leak), which are heated during the descent to 20° C above the ambient gas temperature. Microvalves rated for a wide temperature range (-20° C to +300° C) terminate the flow into the ion source.

The first inlet system operates from approximately 60 km above the surface of Venus down to the cloud layer. The second inlet operates from below the cloud base to the surface of Venus. During the majority of the approximately one hour descent, gases are introduced directly into the ion source of the quadrupole mass spectrometer. However, for a fixed period inclusive of cloud layer passage, the inlets are closed and gases are sampled instead from an internal gas processing system (GPS) loaded with a fraction of the atmosphere admitted via the first inlet. The GPS is specifically designed for the measurement of noble gases and nitrogen. These measurements are achieved through sample enrichment and chemical or physical separation and removal of species that contribute to spectral interference.

The noble gas and nitrogen purification and enrichment cells function as self-contained units. They are charged directly from the ambient atmosphere through a large, low gas impedance filter, a microvalve, and a CO<sub>2</sub> chemical scrubber. The overall gas inlet approach combining filtered flow, parallel capillaries, and line heating, is designed to eliminate any risk of clogging by atmospheric droplets or aerosols.

The dominant CO<sub>2</sub> is chemically removed in the gas processing systems by the scrubber reaction  $\text{CaO(s)} + \text{CO}_2 \rightarrow \text{CaCO}_3\text{(s)}$ . After nitrogen measurements are made, the gas sample is purified by a getter to remove all residual reactive gases. The remaining noble gases flow through a cooled enrichment cell packed with a compound chosen to adsorb krypton and xenon into an evacuated volume. A two-stage thermoelectric cooler (TEC) cools and maintains the cell at -75° C for a short period. After removal of krypton and xenon from the gas phase, argon is removed by opening a valve to the pump. Then the trapped Xe and Kr are thermally released back into the system and analyzed.

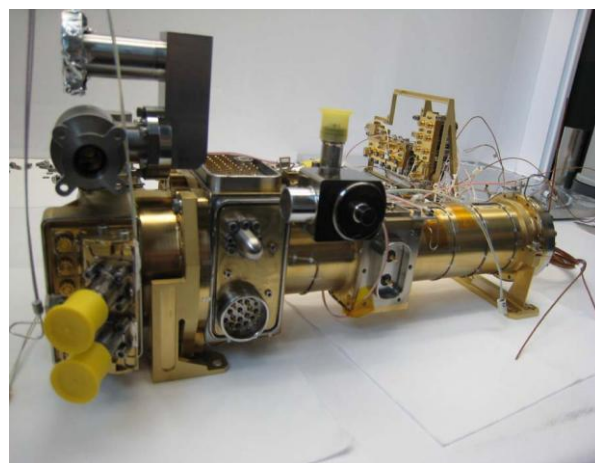
The baseline mass analyzer for NMS is the quadrupole mass spectrometer (QMS) developed for the Sample Analysis at Mars (SAM) suite investigation on the 2011 Mars Science Laboratory [40]. The QMS is a three radio frequency range mass filter based on heritage Goddard designs with precision hyperbolic rods that enable high abundance sensitivity (10<sup>-6</sup> or

lower crosstalk between adjacent peaks) and very stable currents maintained at the center of each mass channel. The SAM flight model QMS is shown in Fig. 3 along with part of the multi-valve manifold of the gas processing system common to SAM and NMS.

The NMS analysis cycle is paced by a standard detector integration time of 30 ms, plus an RF settling time of 3 ms, per mass/charge (m/z) channel. The m/z range is covered through a combination of pre-programmed and dynamically adjusted scans with step sizes of 0.1 Da, 1 Da, or several Da selected as required. The mass analyzer is operated in static mode to eliminate pump-induced errors, leading to greatly improved precision, and an increase in the signal-to-noise ratio (SNR) by more than two orders of magnitude, compared with GPMS.

#### 4. NMS MEASUREMENT CAPABILITIES

The measurements addressed by NMS are listed in Tables 1, 2, and 3 respectively covering noble gases and nitrogen, light element isotopes, and trace gas species. Measurement of the mixing ratios of <sup>20</sup>Ne, <sup>36</sup>Ar, <sup>40</sup>Ar, <sup>84</sup>Kr, and N<sub>2</sub> at Venus will be carried out with an accuracy (i.e., maximum expected uncertainty) of <10%, while that of <sup>4</sup>He will be measured to <5%, and the elemental abundance of xenon expected to be present at a maximum mixing ratio of 2.5 ppb will be measured to <25%. The ratios to <sup>84</sup>Kr of <sup>86</sup>Kr, <sup>83</sup>Kr, <sup>82</sup>Kr, <sup>80</sup>Kr, and <sup>78</sup>Kr will be obtained with an accuracy of <1% while the xenon isotopes <sup>134</sup>Xe, <sup>131</sup>Xe, <sup>130</sup>Xe, <sup>129</sup>Xe, <sup>128</sup>Xe, relative to <sup>132</sup>Xe will be measured to better than 1%. The <sup>126</sup>Xe and <sup>124</sup>Xe are expected to be less than 0.5% of <sup>132</sup>Xe and these ratios will be measured to within 2-5% due to the effect of statistical



**Fig. 3** Flight models of the Sample Analysis at Mars quadrupole mass spectrometer (QMS, foreground) and a subassembly of the gas processing system (background) that may be applied directly in the Venus NMS without significant change. The ~20 cm long circular cylindrical section of the QMS houses the quadrupole rod assembly.

**Table 1** NMS measurement accuracies (maximum expected uncertainty) for the abundances and isotope ratios of nitrogen and noble gases. PV = Pioneer Venus. \*Ne also measured by Venera 13-14.

Gas Species	Mixing Ratio (PV)	NMS Accuracy	NMS Isotope Ratios	PV Value [atom/atom]	NMS Accuracy
N <sub>2</sub>	0.035±0.8%	≤10%	<sup>15</sup> N/ <sup>14</sup> N	0.00383±20	≤1%
<sup>4</sup> He	0.6-12.0 ppm	≤5%	<sup>3</sup> He/ <sup>4</sup> He		≤10%
<sup>20</sup> Ne	9±3 ppm	≤10%	<sup>22</sup> Ne/ <sup>20</sup> Ne	0.085±6%*	≤1%
			<sup>21</sup> Ne/ <sup>20</sup> Ne	unmeasured	≤1%
<sup>36</sup> Ar	30±15 ppm	≤10%	<sup>38</sup> Ar/ <sup>36</sup> Ar	0.18±11%	≤1%
<sup>40</sup> Ar	40±15 ppm	≤10%			
<sup>84</sup> Kr	7-28 ppb	≤10%	<sup>78</sup> Kr, <sup>80</sup> Kr,	unmeasured	≤1%
			<sup>82</sup> Kr, <sup>83</sup> Kr,		
			<sup>86</sup> Kr		
<sup>132</sup> Xe	0.5-2.5 ppb	≤25%	<sup>124</sup> Xe, <sup>126</sup> Xe	unmeasured	≤2%
			<sup>128</sup> Xe, <sup>129</sup> Xe,		
			<sup>130</sup> Xe, <sup>131</sup> Xe,		
			<sup>134</sup> Xe, <sup>136</sup> Xe		

counting errors for these isotopes. The isotope pairs <sup>38</sup>Ar/<sup>36</sup>Ar will all be measured to within 1%. <sup>21</sup>Ne/<sup>20</sup>Ne and the <sup>22</sup>Ne/<sup>20</sup>Ne will be somewhat uncertain since the contribution to the 20 and 22 Da signals from <sup>40</sup>Ar<sup>++</sup> and <sup>44</sup>CO<sub>2</sub><sup>++</sup> are subtracted to secure these ratios. The reactive species listed will be measured with an accuracy of 10-25% with vertical profiles of increasing resolution as the lander slows, achieving complete analyses as frequently as every 200 m in the lower atmosphere. A periodic search will be carried out for previously unmeasured species in the 2-550 Da range.

The analysis of CO presents a challenge to NMS on its own. CO is an important minor species at Venus whose abundance in the lower atmosphere, where photolysis of CO<sub>2</sub> is minimal, is directly linked to the oxygen fugacity of the crust. Its signal at m/z 28 is masked by the dominant contribution to this mass by N<sub>2</sub> which is not possible to separate chemically with any efficiency. The analysis of trace CO is readily achieved by complementary techniques such as TLS (see below), or gas chromatography. The selection of a CO analysis approach is advised by the full range of capabilities available with a second instrument, within the objectives and resources of the mission. For example, the SAGE mission augments the NMS with the TLS to address trace sulfur species in addition to CO. Alternatively the CO could be efficiently separated with a gas chromatograph (GC) subsystem on NMS.

## 5. NMS OPERATION

While the general technique employed by the NMS has been described, it is additionally useful to review the time profile of its operation given the relatively brief descent phase of a mission of such SAGE. The total time available for each segment of NMS operation is determined by the probe entry velocity, the timing of

**Table 2** NMS measurement accuracies (maximum expected uncertainty) for the light element isotopes. PVLP-MS = Pioneer Venus Large Probe mass spectrometer. V11-12 = Venera 11-12 mass spectrometers. IR Spec = Earth-based spectroscopy. Values in brackets indicate improved accuracy with tunable laser spectrometer (TLS). Accuracies for Cl isotope ratio to be determined (TBD) following calibration of current flight instruments against standards.

Isotope Ratio	Gas Species	Previous Measurements		Accuracy NMS [+TLS]
		Ratio	Method	
D/H	H <sub>2</sub> O	0.016±0.002	PVLP-MS	5-10% [ $<1\%$ ]
		0.019±0.006	V11-12/MS	
<sup>12</sup> C/ <sup>13</sup> C	CO <sub>2</sub>	88.3±1.6	V11-12/MS	1-2% [ $<1\%$ ]
		86±12	IR Spec CO <sub>2</sub>	
<sup>16</sup> O/ <sup>18</sup> O	CO <sub>2</sub>	500±25	PVLP-MS	1-2% [ $<0.1\%$ ]
		500±80	IR Spec CO <sub>2</sub>	
<sup>14</sup> N/ <sup>15</sup> N	N <sub>2</sub>	273±56	PVLP-MS	1-2%
<sup>35</sup> Cl/ <sup>37</sup> Cl	Cl <sub>2</sub>	2.9±0.3	IR Spec HCl	TBD
<sup>32</sup> S/ <sup>34</sup> S	SO <sub>2</sub> , OCS, S <sub>n</sub>	None (expect ~0.0443)		$<2\%$ [ $<0.2\%$ ]

any chute deployment and jettison events, and its particular deceleration rates in the Venusian atmosphere. Descent times ranging from 40 minutes to more than one hour have been investigated. An operational script for a short (fast) probe with surface contact 48 minutes after atmospheric entry is given here as an example design-driving scenario. Table 4 provides a summary of the major NMS-specific events synchronized to the descent profile.

**Table 3** NMS measurement accuracies (maximum expected uncertainty) for expected and possible trace species. PV = Pioneer Venus Large Probe mass spectrometer. VenSP = Venera 11-14 Spectrophotometer. GaIR = Galileo IR spectrometer. VenGC = Venera 11-12 Gas Chromatograph. VegUV = VeGa UV Spectrometer. EBIR = Earth-based IR.

Gas Species	Previous Measurements			Accuracy NMS [+TLS]
	Concentration	Altitude	Method	
H <sub>2</sub> O	30±15 ppm	0-45 km	PV, VenSP, GaIR, EBIR	$<25\%$ [ $<5\%$ ]
	30-70 ppm	0-5 km		
SO <sub>2</sub>	150±30 ppm	22-42 km	PV, VenGC, VegUV, EBIR	$<10\%$
	25-150 ppm	12-22 km		
OCS	4.4±1 ppm	33 km	EBIR	$<25\%$ [ $<2\%$ ]
H <sub>2</sub> S	±2 ppm (?)	$<20$ km	PV	$<25\%$
H <sub>2</sub> SO <sub>4</sub>	(present)	clouds	EBIR	*
S <sub>n</sub> (n=1-8)	20 ppb	$<50$ km	VenGC	*
HCl	0.6±0.12 ppm	cloud top	EBIR	*
	0.5 ppm	35-45 km		
Cl <sub>2</sub> , SO <sub>2</sub> Cl <sub>2</sub> , SO <sub>3</sub> , NO, NH <sub>3</sub>	unknown			*



Following atmospheric entry and an NMS warm-up in step #1 and background operation (step #2), the instrument is exposed to the upper atmosphere via breakoff of the Inlet 1 metal to ceramic to metal seal. In steps 3-7 the ion source directly samples the atmosphere through capillary leak CL1. The volume of gas ingested in step #8 is processed in the Gas Processing System (GPS) to chemically remove the CO<sub>2</sub>. Following the measurement of nitrogen, argon, and neon and their isotopes in steps 10-15, these gases are pumped from the GPS and precision Kr and Xe measurements made in a static mode (steps 17-18) by releasing a portion of these gases from the cryotrap. After these dedicated noble gas experiments the second direct inlet is actuated to enable direct atmospheric sampling all the way to the surface (steps 19-20).

## 6. ARCHITECTURE OPTIONS

NMS readily achieves the stated objectives as a standalone instrument operating within the descent profile timeline. This approach is arguably the simplest implementation of a detailed chemical analysis that addresses the top atmospheric science goals at Venus.

The mass of NMS hardware described including all electronics and harness is approximately 12 kg, and the net average power dissipation, for this continuously scanning descent scenario, is approximately 60 W including some margin. With the resources invested to support the NMS investigation, including probe volume, high-reliability controlled gas ingestion, power and high speed data processing electronics, and frankly the infrequency of Venus mission opportunities, it is scientifically and practically responsible to consider additional measurement capabilities that are readily accomplished with instrumentation that is complementary to NMS. As demonstrated by the development of the SAM suite for MSL, the inclusion of a tunable laser spectrometer along with NMS offers an incredibly powerful enhancement of science return without overburdening spacecraft requirements. The TLS is a multi-pass (Herriott cell) infrared absorption spectrometer that offers quantitative analysis of trace gas-phase species introduced to the cell volume. Continuous wave laser radiation, narrowly tunable across absorption features of the species of interest, is directed into the cell and then reacquired after several dozen internal reflections yielding a path length of several meters. Abundances of key selected species and their precise isotope ratios

**Table 4** Example operational profile of a neutral mass spectrometer during probe descent from 66.6 km altitude to the surface of Venus (assumed here to be 0 km altitude). Model atmospheric density given for reference. Valve numbers refers to gas flow diagram in Fig. 2.

t (s)	Duration (s)	Alt (km)	v (m s <sup>-1</sup> )	ρ (kg m <sup>-3</sup> )	Probe Status	NMS Mode	Step	NMS Operations
10	120	66.6	25.8	0.27	atmospheric entry jettison heatshield, deploy chute		1	Power up QMS and other subsystems
130		64.3	18.1	0.33			2	Background scans and other preps
	361					Inlet 1 Continuous Dynamic MS plus Collection	3	Open BOC #1 shortly after heat shield jettison
							4	Gas flows into inlet #1 through flow restrictor toward MS
							5	Flow split with majority of gas going into line with V2 open, into inlet 1 exhaust volume + getter, via second FR
							6	Small amount of gas transits capillary inlet to MS ion source Note: The leaks and volumes are sized such that there is no stagnation in inlet 1 and it remains well mixed
							7	QMS recording continuously
							8	A slug of gas is then admitted into the GPS (V4 w/V2) and admitted to the CO2 scrubber via V9
180	0	63.4	17.4	0.35	jettison chute			
491		40	47.2	2.94	above cloud deck		9	Start GPS gas operations, V1 is closed stopping all Inlet #1 operations (this should occur around 40 km)
							10	After a period of CO2 scrubbing w/V3 and V9 closed, the remaining gas is admitted to the QMS via V5 + capillary inlet
							11	Nitrogen abundance and isotope ratios are measured for some period in direct mode
							12	V5 is closed and V8 opened to admit remaining N2 to the getter which traps the remainder quantitatively
							13	V8 is closed and an additional slug of residual gas (mostly Ar) is admitted via open/close of V5
							14	Ar and Ne abundance and isotopes are done with the high concentration reached using BA gauge to trigger
							15	V5 closed and V6 opened to the NGT to trap out Kr and Xe (does not trap lighter NG) for preprogrammed period
							16	V6 closed and V10 opened to pump away all residual gas, mostly Ar, to clean system for Kr and Xe mmnts
							17	V10 closed and V5 reopened to admit Kr and Xe up to as high a concentration as possible, to measure abundances and isotopes
							18	End of GPS operations. V5 and others reconfigured. Total GPS NG measurement time up to 10 minutes
1091	1803.5	21.8	20.6	15.31	below cloud base	Inlet 2 Continuous Dynamic MS (Trace Species focus)	19	Open BOC #2 to admit gas for trace species runs; continuous direct beaming + QMS standard and smart scanning
2895	0	0	7.7	110.13	landing		20	End of baseline operations (surface operations not assumed)

of H, C, O, and S are thus measured with exquisite sensitivity. Reviews of the TLS instrument and its measurement capabilities on planetary missions are available [40-43]. Here we simply highlight the Venus-specific objectives that TLS would support on a mission such as SAGE.

Briefly, the TLS with appropriate lasers selected to cover H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, and OCS absorption offers the improvements identified in brackets in Tables 2 and 3. TLS additionally has the capability of quantifying CO as mentioned above. In each case, the mixing ratio of the volatile species is expected to be sufficient for a high precision measurement of priority isotope ratios D/H in H<sub>2</sub>O,  $\delta^{13}\text{C}$  in CO<sub>2</sub>,  $\delta^{17}\text{O}$  and  $\delta^{18}\text{O}$  in all four species, and  $\delta^{34}\text{S}$  in SO<sub>2</sub> and OCS, each of which are sensitive to various escape and/or exchange processes that can strongly guide models of climate history and geologic activity, particularly when used in conjunction with NMS results. TLS would likely operate in parallel with NMS. It could employ a dedicated breakoff cap and inlet (Fig. 2) or potentially share one or both NMS inlets with additional valving. Collection of atmospheric samples into TLS followed by signal integration would likely support several TLS analysis cycles during descent through the lower atmosphere, complementing the even finer vertical profiles obtained with NMS in this region.

Beyond the descent probe scenario, other platforms and mission concepts could readily use the NMS (or NMS + TLS) in a similar way and to offer new measurement opportunities. A balloon-type mission [44,45] would deploy the NMS from a gondola platform that circumnavigates Venus, offering weeks of analysis time, rather than an hour, and probing regional as well as global composition. The balloon platform could be deployed on a focused atmospheric mission as well as on a more involved flagship mission that includes a long-lived surface payload [46]. A surface mission could use NMS to analyze surface materials, with an appropriate sampling strategy, yielding a major leap in our knowledge of Venus geochemistry. Development of key technologies for a "Sample Analysis at Venus" (SAV) concept is already underway on various levels; it is not too early to begin planning how it could work in some detail on a realistic mission. Venus awaits!

## 7. REFERENCES

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